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CMC BEHAVIOR AND LIFE MODELING WORKSHOP SUMMARY REPORT (PREPRINT)

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14. ABSTRACT
The Ceramic Matrix Composite (CMC) Behavior and Life Modeling Workshop was held in Dayton, Ohio at the Hilton Garden Inn (3520 Pentagon Park Blvd, Dayton, Ohio, USA 45431) on August 3-4th, 2011. Leaders from the major aero jet engine manufacturers, airframe structure manufactures, and government researchers working on the development and use of CMCs for hot structures were invited to the workshop along with several experts from academia to discuss the current state-of-the art in CMC behavior and life modeling and help to prioritize investment for current critical capability gaps. Industry was specifically tasked to explain where they are at generally in terms of their development of adequate behavior and life models for insertion of CMC components into service and identify critical areas that require investment. Government and academic experts in the field were charged with describing the various approaches currently being developed for behavior and life models for CMC and their immediate applicability in an industrial setting.

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CMC Behavior and Life Modeling Workshop Summary Report

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Workshop Summary

The Ceramic Matrix Composite (CMC) Behavior and Life Modeling Workshop was held in Dayton, Ohio at the Hilton Garden Inn (3520 Pentagon Park Blvd, Dayton, Ohio, USA 45431) on August 3-4th, 2011. Leaders from the major aero jet engine manufacturers, airframe structure manufactures, and government researchers working on the development and use of CMCs for hot structures were invited to the workshop along with several experts from academia to discuss the current state-of-the art in CMC behavior and life modeling and help to prioritize investment for current critical capability gaps. Industry was specifically tasked to explain where they are at generally in terms of their development of adequate behavior and life models for insertion of CMC components into service and identify critical areas that require investment. Government and academic experts in the field were charged with describing the various approaches currently being developed for behavior and life models for CMC and their immediate applicability in an industrial setting. The importance of taking a holistic integrated computational materials science and engineering approach (ICMSE) to materials development and component design was emphasized along with the need to develop information rich experiments for the verification and validation of material models. Multiple discussion periods were inserted throughout the program to enable all participants a chance to offer input. Additionally, all participants were encouraged to contact the technical organizing POC via email to follow-up on what was discussed and provide any additional information they felt important.

Objectives

1. Industry was to define their current and future behavior and life modeling requirements for the Integrated Computational Materials Science and Engineering (ICMSE) of CMCs. Specifically, industry was encouraged to identify and compare modeling and design tools to aid routine design versus those that will be used for specialized material development and evaluation. Some prioritization by industry was also desired regarding the operant damage mechanisms (e.g.,

creep, fatigue, dwell fatigue, environment) for various industrial applications. Additionally, industry was encouraged to specify any current limitations of the available CMC characterization and NDE techniques.

2. Academia and various national laboratories (e.g., AFRL, NASA) were to review the status of the various CMC modeling approaches they are developing, along with their weaknesses and limitations. Specifically, the presenters were to consider the various approaches being developed to model the various damage mechanisms including creep, fatigue and dwell fatigue. In particular, models that can account for the influence of the distributed microstructure on the operant damage mechanisms were to be particularly emphasized. Additionally, models accounting for the influence of environment, residual stresses, temperature gradients and biaxial loading on the various damage mechanisms were to be reviewed and discussed.

Findings

1. **Requirements of CMC Modeling Tools for Industry.** Industry is most interested in insightful models that are transparent and fast. There is less interest in models based on curve-fitting or empiricism which do not capture any of the underlying physics (e.g., neural networks). The industry is would like academia and government researchers to provide models for lifing under fatigue, creep and environmental loading, with clear linkages to the material microstructure, and that are sensitive to statistical variations within the microstructure. However, generally industry is not ready to share databases or any significant material information for the development of these models. There is likely a distinction between tools that will be required for routine design of components versus the actual development of a new material system. Tools that will be used for component design will need to be robust and sufficiently computationally efficient such that they can be exercised in a typical design optimization loop. Tools that will be developed for detailed materials development and analysis, will be used mostly by the material scientists and engineers, be sensitive at the scale of the material structure that is most important to the operant mechanisms of the damage response (e.g., grains, fibers, porosity), and be robust enough to consider a wide range of material variants. The data from the physically based microstructural scale models could likely be used to inform simpler higher scale models for component design. The greatest need and perhaps significant challenge is to develop models calibrated with coupon data that can then be readily applied evaluate components.
2. **Prioritization of Damage Mechanisms.** Creep, fatigue and environmental concerns are all very important for hot structures, but priority of importance will depend on the specific component of interest (e.g., engine shroud, turbine blade, TPS panel). The interlaminar properties across all the various CMC systems are not well understood, particularly at higher temperatures because of the experimental challenges in characterizing them. Monotonic testing generally lacks

relevance for most industrial applications and priority should be placed on understanding cyclic loading and loading under multiaxial stress states. Resources should be exercised to develop appropriate standards and testing procedures to capture damage under these more complex loading conditions (e.g., cyclic, multiaxial), which often require more expensive non-standard testing (when compared to metals). Joining and bonding will have a critical influence in the component response and must be considered early on.

3. **Intellectual Property.** It would be advantageous to identify specific pre-competitive areas where industry can work together in the development of behavior and life models and modeling strategies for CMCs. As industry has expended extensive company resources to develop various CMC materials, there is significant sensitivity regarding the processing and chemistry of the specific CMCs developed by the various companies. As a result, it is not likely that collaboration will be forthcoming regarding materials development, process modeling, or process control. However, in many cases the environmental degradation and damage mechanisms can be similar and it is likely that behavior and life models and approaches will be applicable across a broad range of systems. The reliability assessment code DARWIN™ (Design Assessment of Reliability With Inspection) that has been developed by the Southwest Research Institute® and four of the major gas turbine manufactures to assess failure of rotor disks was brought up as an example of such a pre-competitive effort that has been a success. Similar lifing and assessment codes for CMCs could be similarly developed at a pre-competitive level and aid in the eventual insertion of CMCs into real components. It was recognized and understood even before the workshop was held that proprietary information would not be shared in an open forum such as this workshop. However, it was suggested during the workshop by multiple participants that it would be beneficial to arrange additional closed follow on meetings between individual industry representatives or a single industry consortium, the government, and other select academic partners.
4. **Engineering Expertise in the Modeling of CMCs.** There is a specific need in industry for engineers and machinations that both understand applied mechanics and have a physical understanding of the material. Such a physical understanding often comes through personal experience working in the laboratory on various testing programs. Often modelers are not trained with any laboratory experience and a disconnect results between the modelers and physical system. In general, funding for research in ceramics matrix composites at the university level is limited and only a handful of universities have active research in the area. As a result the number of students graduating with any experience with ceramic matrix composites is limited.
5. **Discrete Damage Models.** Various approached are being pursued to account for discrete cracking events; however, in general all these approaches lack maturity. It is not clear at this stage whether these approaches will work for routine design due to their current complexity or if they will be more limited to materials development and evaluation. Methods to verify and validate these models are largely absent and will require extensive thought and investment. Additionally, a better understanding of the mesh sensitivity to the approaches based on cohesive elements or on the extended finite element approach (XFEM) is required. In many

cases, cohesive laws are required, which can be hard to define and calibrate on the scale of the actual dominate attributes of the microstructure. It is possible that the greatest utility for such discrete damage models will be to explore specific “hot spots” or features as part of a more hierarchal or multiscale framework. For example, one my simulate the details of a notch root using a more high fidelity model like a discrete damage model while the rest of the component is simulated using a more computationally efficient continuum approach.

6. **Continuum Damage (or Multiscale) Approaches.** FEM based continuum approaches are the most likely to be used by industry in the short term because such approaches are the most similar to the approaches used in current industrial design systems. However, in most cases there is a lack of verification and validation for physically based microstructure-sensitive continuum models. Although such models are calibrated to and capture the macroscopic stress-strain response, in most cases similar information at the microscale is unavailable. Therefore, an understanding of how well these model actually capture the microscale response is lacking. Until such verification and validation of these types of microstructure-sensitive approaches can be accomplished, confidence in the results must be considered with caution. Moreover, justification for a microstructure-sensitive modeling approach versus a traditional empirically based engineering model will be brought into question until such validation is possible. Many of the continuum based approached discussed, are based on the concept of a representative volume element; however, in most damage processes a representative volume element does not exist. The life limiting damage will always initiate at the weakest link in the material, creating a needle in the haystack or extreme value type problem. It is not likely that a RVE based approached can be employed to model damage process dependent on the extreme value statistics of the material structure.
7. **Environmental Damage Models.** The current understanding of environmental degradation in SiC/SiC composites is limited. Work is ongoing in industry to understand the role of the environment in SiC/SiC composites, but many of the results have been deem proprietary and is not available in the public domain. To the knowledge of the technical organizer of the workshop, as of the date of this meeting the University of Virginia is the only academic institution with an active research group working on modeling the influence of the environment on CMCs. Understanding the role of environment is essential to the industrial use of CMCs.
8. **CMC Characterization Methodologies.** There is a wide range of techniques available to characterize the environmental degradation and the mechanical response of CMCs. More work needs to be done to standardize the verification and validation of microstructure sensitive behavior and life models for CMCs. Developing routine testing at elevated temperature will be essential to understanding the material and for calibration and validation of behavior and life models.
9. **NDE Techniques for CMCs.** Although there are many NDE methods available, little work has been done to explore the application of existing methodologies to characterize damage in CMCs.

10. **Process Modeling.** Although the topic of process modeling was not specifically covered during any of the sessions, it was brought up repeatedly as a area of importance during multiple discussion periods. In general, most processing and materials development activities for CMCs have been done by industry and are considered to be proprietary. As a result, there is little information available in the open literature that can be used to develop process models in government laboratories or in academia. Therefore, process modeling will most likely be driven by industry as an effort to increase process control and process yields. The highly sensitive proprietary nature of most processing for CMCs leaves in doubt the ability for the government or academia to drive specific process modeling efforts unless they are supported by industry through various negotiated agreements

Workshop Program and Participants

The workshop was divided into five sequential sessions:

1. CMC Design Practices/Tools for Gas-Turbine Engines and Aircraft Structures
2. Discrete Damage Models
3. Environmental Models
4. Continuum (and/or Multiscale) Damage Models
5. CMC NDE and Characterization for ICMSE

Each session was followed by a discussion period. Two keynote addresses were given, one on each day, focusing on various aspects of Integrated Computational Materials Science and Engineering (ICMSE). All of the presentations that were given were made available to all participants after the meeting from the workshop organizer, Tia Christie at UES, Inc.

Keynote Addresses (title, name, affiliation)

- *ICMSE* - Dennis Dimiduk (dennis.dimiduk@wpafb.af.mil), Air Force Research Laboratory
- *A Pipeline for Virtual Tests* - Brian Cox (bcox@teledyne.com), Teledyne Scientific Co LLC.

Invited Talks (title, name, affiliation)

SESSION 1: CMC Design Practices/Tools for Gas-Turbine Engines and Aircraft Structures

- *CMC Model Development Needs: Application to Component Design and Material Development,* Doug Carper (doug.carper@ge.com), GE Aviation
- *CMC Behavior and Life Prediction at Pratt & Whitney,* Kevin Rugg (kevin.rugg@pw.utc.com), Pratt & Whitney
- *Rolls-Royce CMC Design Perspectives,* Thomas Cook (thomas.s.cook@rolls-royce.com), Rolls Royce
- *Making the case for improved characterization, modeling, and lifing of CMCs* - Todd E. Steyer (todd.e.steyer@boeing.com), Boeing Co.

- *Design of CMC Components at Lockheed Martin Aeronautics* - Doug Gaudin (doug.r.gaudin@lmco.com), Lockheed Martin Co.

SESSION 2: Discrete Damage Models

- *Stochastic fiber-scale models: failure, processing science, and the butterfly effect*, Qingda Yang (qdyang@miami.edu), University of Miami
- *Discrete Damage Simulation in Polymer Matrix Composites: Research Efforts at the Air Force Research Laboratory*, David Mollenhauer (david.mollenhauer@wpafb.af.mil), Air Force Research Laboratory
- *Impact Damage Simulation of Layered Materials Using Peridynamic Theory,* Erdogan Madenci (madenci@email.arizona.edu), University of Arizona

SESSION 3: Environmental Models

- *Environmental Damage Mechanisms and Modeling*, Beth Opila (ejo4n@eservices.virginia.edu), University of Virginia
- *Environmental Effects in SiC/SiC composites*, Ron Nimmer (nimmer@ge.com), GE Global Research

SESSION 4: Continuum (and/or Multiscale) Damage Models

- *Key Issues in Modeling the Mechanical Response of CMCs*, Robert Goldberg (robert.goldberg@nasa.gov), NASA Glenn Research Center
- *Fundamental Issues in Modeling of Mechanical Behavior of CMCs*, Ramesh Talreja (talreja@aero.tamu.edu), Texas A&M University
- *Multiscale Design System*, Jacob Fish (fishj@columbia.edu), Columbia University
- *Homogenization Based Continuum Damage Mechanics Models for Composites in Monotonic and Cyclic Loads*, Somnath Ghosh (sghosh20@jhu.edu), Johns Hopkins University

SESSION 5: CMC NDE and Characterization for ICMSE

- *Challenges in Performing Relevant, Information-Rich Experiments on CMCs*, Frank Zok (zok@engineering.ucsb.edu), University of California Santa Barbara
- *Use of Acoustic Emission and Electrical Resistivity to Monitor Damage Development in CMCs*, Greg Morscher (gm33@uakron.edu), University of Akron
- *The Status of NDE for CMC's,* Adam Cooney (adam.cooney@wpafb.af.mil), Air Force Research Laboratory

Session Chairs (Session Title, Name, Affiliation)

- *CMC Design Practices/Tools for Gas-Turbine Engines and Aircraft Structures*, Michael Kinsella (Michael.kinsella@wpafb.af.mil), Air Force Research Laboratory

- *Discrete Damage Models*, George Jefferson (George.Jefferson@wpafb.af.mil), Air Force Research Laboratory
- *Environmental Models*, Randy Hay (randall.hay@wpafb.af.mil), Air Force Research Laboratory
- *Continuum (or Multiscale) Damage Models*, Triplicane Parthasarathy (Triplicane.Parthasarathy@wpafb.af.mil), UES Inc.
- *CMC NDE and Characterization*, Larry Zawada (Larry.Zawada@wpafb.af.mil), Air Force Research Laboratory

Participants

This workshop was attended by 95 persons, including speakers from academia, government laboratories and industry. All of the speakers were from organization located within the United States of America.

Academic Institution Representation: There were a total of sixteen academic institutions represented including: Columbia University, Johns Hopkins University, Massachusetts Institute of Technology, Rice University, Texas A&M University, The University of Toledo, University of California Santa Barbara, University of Akron, University of Arizona, University of California Berkeley, University of Florida, University of Miami, University of Michigan, University of Texas at Arlington, University of Virginia, and University of Wyoming.

Government Laboratory Representation: There were a total of three government laboratories represented including: Air Force Research Laboratory, NASA Glenn Research Center, and NASA Langley Research Center.

Industry Representation: There were a total of twenty one industrial organizations represented including: Aerospace Business Development Associates, AlphaSTAR Corporation, ATK, Boeing Company, Evisive, GE Aviation, GE Energy, GE Global Research, Honeywell Aerospace, Rolls-Royce Corporation, Lockheed Martin Aeronautics Company, Material Research and Design, Materials Sciences Corporation, Multiscale Design Systems, Pratt and Whitney, Scientific Forming Technologies Corporation, Structural Analytics, Teledyne Scientific, UES, United Technologies Research Center, Wildman Consulting.

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